

Using Virtual Reality for assessing the role of noise in the audio-visual design of an urban public space

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ABSTRACT:

Sound planning is not often included in the urban design process despite the well-known audio-visual interactions of human perception. A methodology to compare the overall appreciation of future renovation alternatives of urban public spaces using Virtual Reality Technology is proposed. This method is applied to assess the role of noise in the overall appreciation of a walk on a bridge crossing a highway. The auralization is a dynamic 3D surround based on B-format recordings (ambisonics), filtered by means of full-wave numerical calculations obtaining the sound field behind noise barriers along the bridge's edge. Four different styles of visual street design including different noise barrier heights in combination with the 4 corresponding predicted sound fields were evaluated for their pleasantness by 71 normal-hearing participants on 4 separate days. Each day participants experienced all the visual environments with only one soundscape (to elude direct sound comparison) and anything related to sound was not mentioned in the first part of the experiment. Even in this non-focussed context, a statistically significant effect of the sound environment on the overall appreciation was found. In general, the pleasantness increases with traffic noise level reduction, but the visual design has a stronger impact. By mentioning the soundscape while introducing the evaluation, slightly lower (but statistically significantly different) pleasantness ratings were obtained. Instead of increasing noise barrier height, improving the visual design of a lower barrier seems more effective to increase pleasantness. Visual designs including vegetation strongly outperform others. The virtual experience was rated as immersive and realistic.

INTRODUCTION

The fact that soundscape is not commonly taken into account in urbanism might contribute to the ubiquitous noise problem in our cities nowadays (Bild, Coler, Pfeffer, & Bertolini, 2016).

Similarly, when visual quality is not given sufficient attention in acoustic interventions, the result might even be a worsening of the general environmental quality of the urban space. The lack of simultaneous consideration of both visual and sound may give rise to inefficient interventions in urban areas, often resulting in disuse of public spaces by pedestrians. Any urban renovation should be at the disposal of pedestrians from a holistic point of view, taking into account all the elements affecting activity in the urban context.

The combined audio-visual influence on human environment perception is known since long. The study of Southworth (Southworth, 1969) showed for the first time how sounds influence perception of the visible city, concluding that sound has the function of enriching the environment. Recent studies further showed how sound and visual interaction affect perception. Auditory perception improves when accompanied by visual cues, and similarly, sounds can direct attention to related visual elements (Carles, Barrio, & De Lucio, 1999; Boadbent, 1958; Hong & Jeon, 2014; Joynt & Kang, 2010). The effects of non-auditory factors on soundscape perception has been investigated concluding that urban soundscape is dominated by acoustic comfort, visual images and day lighting (Jeon, Lee, Hong, & Cabrera, 2011). Natural green to improve noise perception takes a special place in this context. Natural features are indicators of tranquillity (Pheasant, Horoshenkov, Watts, & Barrett, 2008). The view on vegetation as seen from a living room's window facing a city ring road was shown to strongly reduce the self-reported noise annoyance (Van Renterghem & Botteldooren, 2016). Aylor found that there was a 7 dB difference in the perception of loudness between hemlock trees and a minimal fence

obscuring an acoustic source (Aylor, 1977). Also traffic noise can influence the perceived visual impact of motorway traffic, especially in a natural landscape (Jiang & Kang, 2016). The visual perception of traffic was shown to have a significant influence on perceived noise, increasing the average ratings of noisiness where the degree of visual screening was higher (Watts, Chinn, & Godfrey, 1999). Perceived loudness and noise annoyance was found to be lower for transparent noise barriers than for opaque barriers (Joynt & Kang, 2010; Maffei, Masullo, Aletta, & Di Gabriele, 2013). Certain sounds like traffic noise and especially bird song are rated more negatively the more urban the visual setting is (Viollon, Lavandier, & Drake, 2002). The effects of visual characteristics in landscapes on soundscape perception in city parks was studied, concluding that the percentage of buildings, vegetation and sky in panoramic views were landscape elements effectively influencing soundscape perception (Liu, Kang, Behm, & Luo, 2014).

These findings are guiding towards an assessment method for design and renovation of urban public spaces that fully accounts for coupled audio-visual perception. State-of-the-art Virtual Reality technology is facilitating this objective, simulating the user's physical presence in a virtual replication of a real environment, and allowing the interaction with the urban space. Some recent studies have already used VR to simultaneously assess sound and visuals in the perceived urban environment (Aletta, Masullo, Maffei, & Kang, 2016; Maffei, Iachini, et al., 2013; Maffei, Masullo, et al., 2013; Ruotolo et al., 2013).

However, to fully unleash the possibilities opened by modern VR, a few factors in the audio-visual experience need to be considered carefully. Firstly, a realistic audio-visual interaction needs to include movement as we do in real life (Nordahl, 2006), where people walk and move the head around willingly to explore the environment. Previous research has concerned

acoustically static environments based on binaural recordings from a fixed head position (Maffei, Iachini, et al., 2013; Ruotolo et al., 2013). Achieving a virtual dynamic acoustic ambiance is especially difficult for non-existent soundscapes that need to be auralized and reproduced in a 3D soundscape. Secondly, the daily use of the public urban space usually does not involve active listening (Lindborg, 2015). Hence it could be expected that assessment of urban designs may be affected by focussing attention of the participants on the sound environment. It was also observed that landscape preference varies when being informed about the context (van der Wal et al., 2014). This would imply that a very careful experimental design is needed to guarantee ecological validity of this assessment.

In this paper, a method for 3-dimensional auralization of future sound interventions is proposed, allowing simultaneous interaction with the user's head movement. Furthermore, physical movement within the virtual environment is possible, allowing the user to walk, perceiving the changing visuals and changing soundscape along the journey and having the possibility to look around freely and localizing in space the different sound sources. The design of the future soundscapes in an urban renovation can include noise abatement measures. The proposed method modifies the existent urban sound recorded in B-format (ambisonics) according to an accurate calculation of the correspondent frequency-dependent insertion loss by means of a full-wave technique: the Finite Different Time Domain (FDTD) method is used here. An existent bridge over a highway is considered as a case study where this method is put into practice. This methodology is fully explained in Section 1.

In this paper, the above methodology is applied to investigate the influence of highway traffic noise on the overall pleasantness of experience of walking towards the park, in particular when the users of the space are not made aware of the presence of this sound. As subliminal sound was

shown to influence perception (Kang & Schulte-Fortkamp, 2016), some effect is expected. An experiment was conducted with 75 participants (that had no prior knowledge of the place) to compare the quality of different urban renovation proposals. The experiment was carefully designed to achieve ecological validity needed to assess the different renovations in the same urban scenario, recreating a realistic experience in a lively surrounding of a city created with elements in motion (cars moving, trams passing by and people walking). In a first phase, the same sound environment was present during the presentation of all designs but the same evaluation was repeated during different days with a different sound environment. This experimental design strongly reduced the awareness of the differences in the sound environment. In a second part of the experiment participants were asked to specifically pay attention to the different visuals and sounds (informed). Section 2 discusses the results of this experiment.

1. METHODOLOGY

1.1 General methodology

A new methodology is proposed to compare the quality of future urban renovation alternatives for an urban street area by means of Virtual Reality, including the sound planning strategy. VR artificially replicates an environment allowing user interaction in 360 degrees. The immersion is experienced through different sensory modalities providing the perception of being physically present. This method uses the full-sphere surround sound of the existent soundscape of a current noisy area, and auralizes future urban renovations. VR allows to walk immersed through an urban environment with the freedom to look around as we do in normal life, ensuring sufficient ecological validity. This presentation of the sound environment goes far beyond the more common binaural presentation that limits the movement of head. The freedom of the user to

move the head while walking in a virtual scene forces to build a dynamic 3D sound environment (ambisonics). The headphone playback requires instant head tracing and accounting for average Head Related Transfer Function HRTF.

The visualization of the urban area can be built in any 3D software or Game Engine and reproduced with any head-mounted device to provide the virtual visual experience. The necessity to reproduce a realistic feeling in the users requires a detailed and accurate visual and audio model as similar as possible to the real urban area.

The auralization process of the renovation starts from a 4 channel B-Format recording of the existing sound environment, which allows to include auditory spatialisation partially due to the limited directivity of the first order channels of ambisonics. It is however enough to provide a feeling of sound immersion while keeping the mobile sound recording relatively straight forward. The urban intervention might include noise abatement measures whose corresponding noise reduction needs to be calculated in detail, resulting in a frequency-dependent insertion loss used for filtering the aforementioned B-Format recordings. In this work, the detailed finite difference time domain (FDTD) method was used to numerically predict the effect of different noise barriers (Ding, Van Renterghem, & Botteldooren, 2011). This accurate method is capable of computing all physical phenomena involved like multiple diffractions and scattering. This technique has been successfully validated over a wide range of acoustical applications, including sound level predictions in urban streets (Echevarria Sanchez, Van Renterghem, & Botteldooren, 2015). The B-format is decoded in a 3 dimensional reproduction audio system and applied the insertion loss previously calculated. Thereafter, it is implemented within the Virtual Reality model as an equidistant surround sound source system around the character controller associated to the position and movement of the person experiencing the VR. To allow for a dynamic

assessment of the environment (users are moving in the urban environment), the virtual sources for B-Format reproduction move in parallel and simultaneously to the character controller and are synchronized in time and space with the original recording.

In a final step, test persons are asked to make virtual walks through the urban environments to assess their experiences in detail. In the following section this general methodology is applied to a case study.

1.2 Case study

In this paper, the proposed general methodology has been applied to compare the quality of different renovation alternatives of an urban bridge in Antwerp (Figure 1). The bridge was chosen due to its strategic position, crossing the highway R1, and connecting a very densely populated district in the city centre with the only green area easily accessible (Rivierenhof Park). However, the bridge is currently practically in disuse by pedestrians for its unattractive visuals and its high noise exposure (exceeding 80 dB (A)). Furthermore, the bridge gives a feeling of unsafety due to the need to use narrow walkways close to the road. The park is therefore perceived very far from the urban area despite its rather close distance, making the bridge an additional barrier instead of a connector.



Fig. 1. Bridge perspective (Google maps) and aerial view where the endpoints and direction of the walk are indicated.

The renovation aims to recover the connectivity function of the bridge for pedestrians and cyclists. This is achieved by improving safety, landscape and soundscape. Firstly, a rearrangement of the street uses was proposed, merging the walkable and cycling paths at one side of the tram lines, and bundling the parking and driving lanes at the other side of the bridge to separate and increase the distance between the sound sources and the pedestrians and bikers (Figure 2).

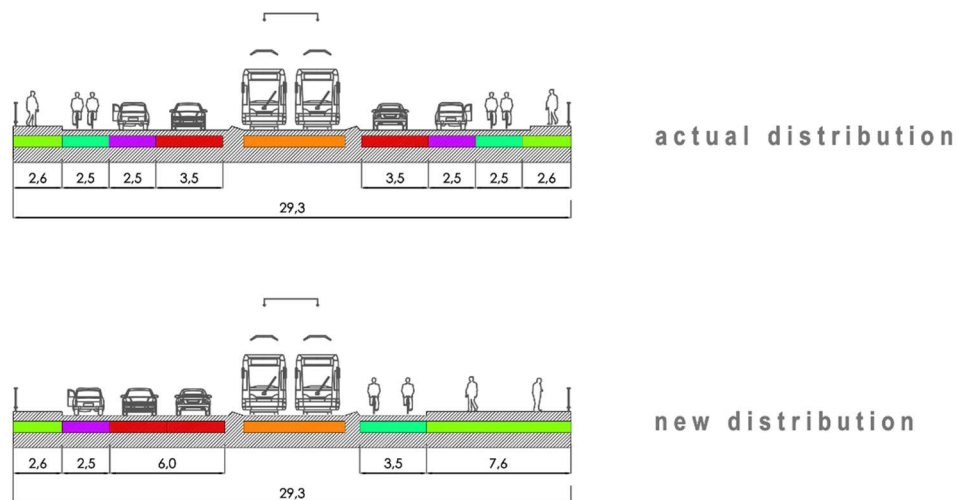


Fig. 2. Street use redistribution on the bridge.

Secondly – and this is the main focus of this paper – different renovation designs were proposed to improve the visual and acoustical quality in the pedestrian area. Visually, different materials and urban furniture were added in four different styles of visual designs (V1, V2, V3 and V4). Acoustically, noise barriers of different heights were introduced in each design to reduce the noise levels on the bridge (S1, S2, S3 and S4).

1.2.1. Visualization

The visualization was created with high detail and realism using the 3D Studio Max software and Unity Game Engine (Figure 3). The Oculus Rift DK2 is the head-mounted device used to provide the virtual visual experience.



Fig. 3. Aerial view of the virtual model and real view from the highway.

The geometry of the terrain, roads, bridges and buildings was built to the likeness of the real visual environment, following a topographical map of the area. The textures are assigned as complementary maps (normal, displacement, occlusion and specular maps). Detailed elements of urban life were added: urban furniture, railings, street lights, manhole covers, bollards, planters, plants and trees. To achieve a real urban environment, the typical life and movement in the city needs to be included. Trams were programmed to slide along the rails, cars and trucks were adjusted to drive on the roads. Special attention was given to the highway R1, since it is the main source of noise when walking on the bridge. Finally, a few virtual humans walking along the walkway were added. The participant is included in the virtual model as the first-person controller. Each participant followed the same route (Figure 1), settled at 3 m from the edge of

the bridge. The walking speed was 5 km/h. Participants had the freedom to move their head both horizontally and vertically to experience the whole environment.

The 4 different Visual designs put to the test were intentionally designed in different styles. They are presented in Fig. 4. V1 was created following a traditional style, V2 shows a modern style, V3 is a vegetated and rural style with careless vegetation and V4 corresponds to a whimsical design.

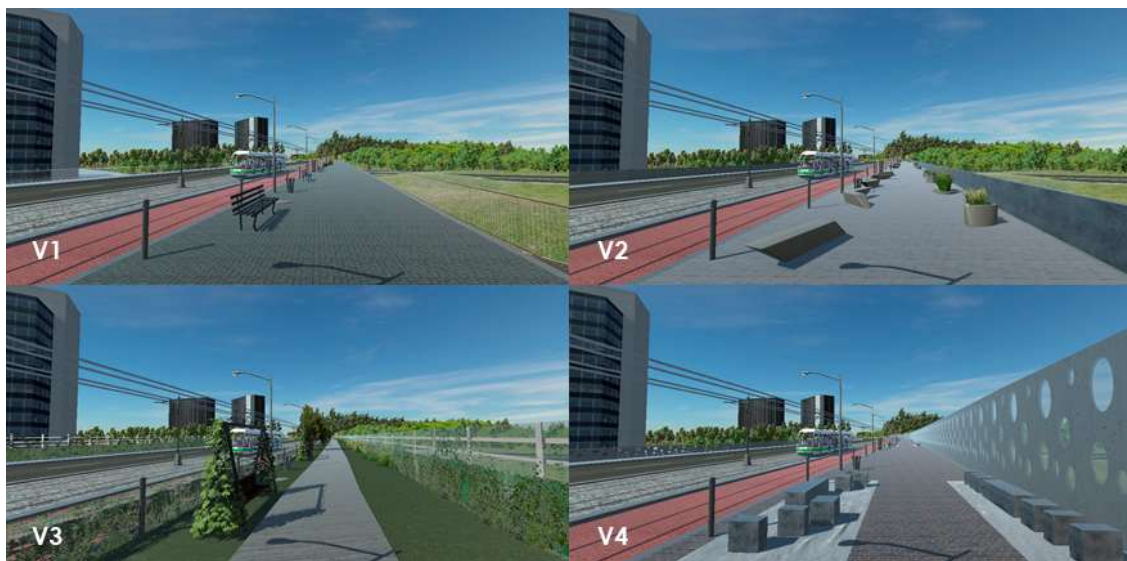


Fig. 4. Four visual designs proposed
V1: Traditional. V2: Modern. V3: Vegetated. V4: Whimsical.

1.2.2. Auralization

Since studying the soundscape is an important target in this research, the audio creation has been carefully developed. Of particular importance is the traffic noise generated by the highway vehicles and the shielding of this noise provided by the different noise barriers.

The four virtual sound environments are the result of the summation of two classes of sounds: the invariable and the variable ones.

The invariable sounds remain identical in the four soundscapes and originate from point sources on the bridge at distinct moments. The sound of the tram, different individual cars passing by and the sound of the character controller's footsteps form this group. They are monaural recordings applied directly in the virtual model as a single source attached to the moving source element. These sounds add realism to the bridge's virtual sound environment. Additionally, they play an important role by providing an auditory frame of reference for the participants (Turchet, Nordahl, & Serafin, 2010; Visell et al., 2009).

The variable sounds correspond to the predicted traffic noise from the highway. They are different in each virtual sound environment and correspond to the traffic noise coming from the highway and received by a pedestrian while walking along the bridge at 3 m from its edge, including the presence of a barrier. These sounds are present all the time during the walk; their intensity depends on the position of the person controller relative to the length axis of the highway. The sound of the highway and the sound of the birds from the park that can be heard at the end of the walking experience are part of this group. These sounds are obtained via a B-Format recording on the original bridge as explained below.

a) FDTD prediction

The highway noise shielding provided by the 3 noise barriers (1.2 m, 2 m and 3 m height) (Figure 5) was calculated for a pedestrian on the walkway, at 3 m distance from the edge of the bridge, corresponding to the first-person controller's position. Due to the high computational cost of the FDTD technique, the calculation was limited to 2 dimensions, which is however suitable for a longitudinal geometry with a constant section like a bridge (Figure 2). In addition, a 2D to 3D correction was applied to account for differences in free field propagation for point and line

sources (Heutschi, 2009). A perfectly reflective material was assigned to all surfaces, including the barriers. It was further assumed that all barriers are perfectly sound insulating (meaning that sound enters the receiver zone by diffraction only). The difference in acoustic performance between the barriers is only due to their changing heights. Sound emission from the highway was modelled as a distribution of incoherent point sources. A horizontal plane of receivers was positioned along the bridge at 1.5m height, with a width of 1 m over which averaging was performed (Table 1).

Table 1.

1m average Insertion loss for pedestrian positioned at 3 m from the bridge edge (dB)

Barrier height (m)	125 Hz	250 Hz	500 Hz	1000 Hz
1.2	-4.5	-4.8	-6.6	-8.1
2	-5.6	-7.0	-9.5	-11.8
3	-5.3	-9.2	-11.7	-13.1

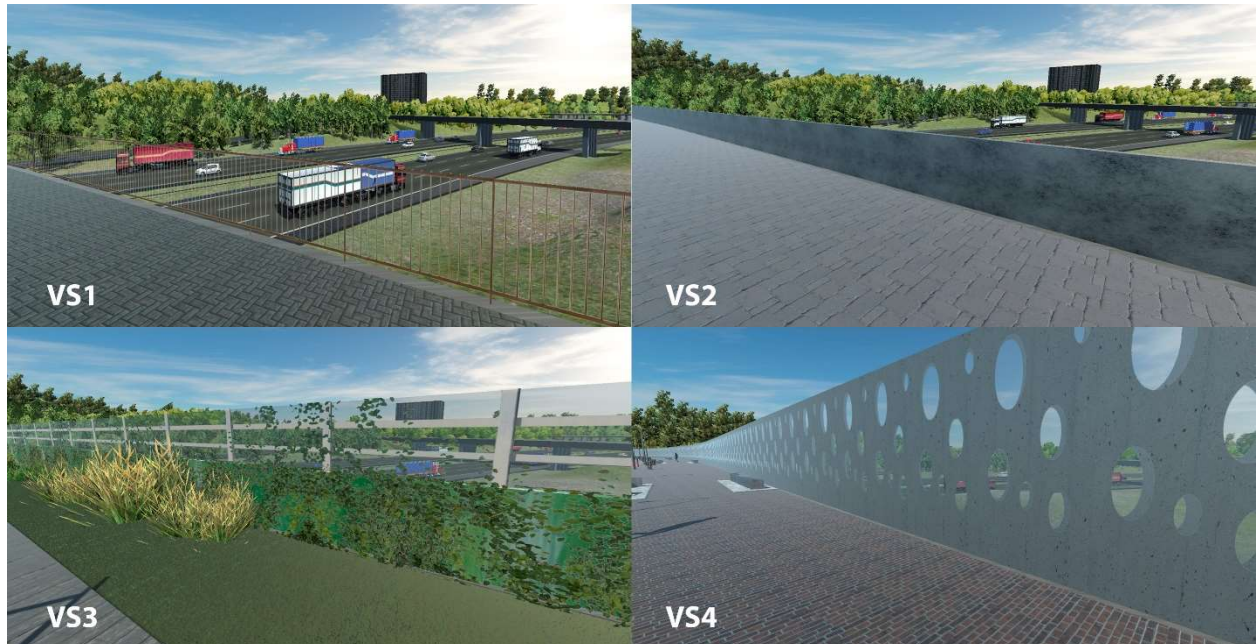


Fig. 5. Four noise barriers and sound environments proposed.

VS1: common rail, no sound barrier. VS2: concrete opaque, 1.2 m barrier. VS3: concrete vegetated with upper part in glass, 2 m barrier. VS4: concrete opaque with oval windows, 3 m barrier.

b) Recording and auralization

A Soundfield ST350 Portable Microphone System was used to record to a B-Format file the current highway traffic noise reaching a pedestrian walking from the beginning (A) until the end of the bridge (B) (Figure 1). Since the bridge under study also carries a lot of local traffic, the recording was made while walking over a nearby pedestrian bridge, ensuring that pure highway noise was recorded. Simultaneously, a calibrated type 1 Svantek 959 Sonometer was used to measure sound level in 1/3 octave bands to set a reference level for the playback of the recording. Additionally, a GPS tracker application for mobile phones stored the geographical position of the route. In the auralization procedure, the B-Format format was decoded as Hexagon format in Visual Virtual Microphone software and converted into 6 mono files to be reproduced by 6 loudspeakers surrounding the listener. The calculated insertion losses of the noise barriers were used to filter these 6 signals.

c) Reproduction

The Unity software is capable of simulating a dynamic audio environment in a 3-dimensional space in real time, reproducing it through a head tracked headphone system. The reproduction of the variable sounds (highway) in Unity consisted in playing back the six mono files through virtual loudspeakers of a plane hexagonal virtual surround audio system. This configuration was preferred over the non-equidistant 5.1 or 7.1 as it has no preference direction and hence the user could move his head also to look backwards. This system does not allow localization outside the horizontal plane. This choice was made because human audition is less sensitive to vertical position, but also because modifying the direction of arrival for sound diffracted over a barrier is

not straight forward. The virtual loudspeakers were located equidistantly around the character controller at 1.5m distance and assigned a parallel movement and speed, correspondent to the recording. No further modification was added within the Game Engine software except for the gradual volume difference between the Audio Sources at the side of the barrier and the ones at the other side of the person controller. The latter were slightly reduced to compensate the width difference between the simulated virtual bridge and the pedestrian bridge where the initial recording was taken. The audio reproduction needed to be synchronized in time and space in the virtual model. The highway traffic intensity and composition near the bridge was estimated based on the moment of the recording. Due to the continuous character of the sound from the busy highway, sound emission from individual vehicles was not modelled since human listeners would not perceive this. The invariable sounds in Unity consisted of mono audio recordings of the different vehicles passing. Since these sounds are not evaluated in the research, the audio accuracy is not so critical hence the auralization for moving sources provided by the Game Engine was used. Finally, good quality headphones (Sennheiser HD280pro) were used for the V.R. audio reproduction.

d) Calibration

The overall sound exposure of the participants crossing the bridge in the VR experiment was calibrated for the no-barrier case. This was done in a quiet room using a B&K head and torso simulator (HATS) type 4128C (Brüel & Kjær, Denmark). The traffic sound from the highway during the virtual walk was registered by the Brüel & Kjær's PULSE LABSHOP software (Figure 6a). The HATS itself was first calibrated using a pistonphone emitting a signal of 124dB for both right and left ear.

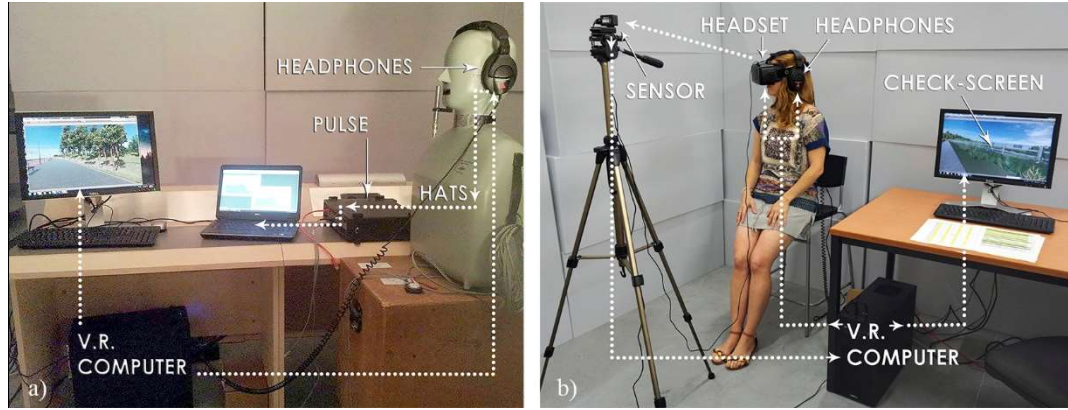


Fig. 6. a) Equipment used for calibration. b) Equipment used for Virtual reality experiment.

The equivalent A-weighted sound pressure level (L_{Aeq}), which was simultaneously measured while performing the B-Format recording on the bridge with a free-field microphone and class 1 measurement equipment, was used to adjust the sound volume in the Virtual Reality reproduction environment with headphones. The L_{Aeq} of the correspondent virtual sound walk (S1) was measured with the HATS looking constantly to the front (parallel with the bridge's edge). The spectra of the virtual walk by the HATS with headphones and the measured free-field microphone showed to be similar, while the L_{Aeq} was very close. Note that for this comparison, the average of the left and right ear of the HATS was taken (Table 2). The L_{Aeq} values measured in the virtual experience (Diff of L_{Aeq} in Table 2) are consistent with the barrier shielding effect calculated with FDTD (Table 1).

Table 2
Calibration of sound exposure via headphones.

Barrier height (m)	L_{Aeq} Left ear dB(A)	L_{Aeq} Right ear dB(A)	Average Left-Right dB(A)	Diff of L_{Aeq} with current case	Difference Right-Left ear
no barrier	76.1	76.9	<u>76.5</u>	—	0.8
1.2	68.0	69.2	68.6	7.9	1.2
2	64.5	66.0	65.3	11.3	1.5
3	63.4	64.8	64.1	12.4	1.4
Measured reference for calibration:			<u>75.8</u>		

1.3. Experiment

1.3.1. Participants.

Participants from 18 to 50 years old were invited to take part in the experiment by means of informative flyers and posters distributed in the city of Ghent. The experiment was performed over a period of two months during summer 2016. The experiment was announced as a living environment experiment using virtual reality and the oculus headset. Sound, acoustics laboratory, and similar words that could indicate the real goal of the experiment were carefully avoided. 75 persons completed the experiment and received a reward of 50 euros. The majority of participants were younger than 35 and highly educated. They were all pointed at the health and safety warnings by Oculus. This study was approved by an independent Commission for Medical Ethics with the registration number BE670201628136 (31-03-2016), and is carried out according to the guidelines of Good Clinical Practice (ICH / GCP) and the Declaration of Helsinki for the protection of people participating in clinical trials. All participants signed an informed consent form.

1.3.2. Schedule.

Participants experienced the predetermined virtual walk over the bridge for the different renovations scenarios. The participants had no control on the exact path, nor on the walking speed. Each walk lasted for 2 minutes and 52 seconds. During the experiment, they sat on an ischiatic support stool to provide safeness while their position is close to standing upright since the VR simulated a walk (Figure 6b). The whole experiment consisted of two distinctively different parts. For the first part, participants were asked to attend on four different days. During

each day, four different visual designs were presented combined with exactly the same sound environment. On the subsequent day, visual designs were kept the same while the sound environment had changed, yet without informing the participants that were led to believe that they were evaluating four slightly different designs. This experimental design eluded direct comparison between the sound environments. Details of the experimental design can be found in Table 3 (day 1, 2, 3 and 4a). Note that this means that on each day only one of the visual designs corresponded to the actual soundscape (the so-called true-combination). The order of presentation of both the visuals and the sounds were randomized between participants.

The second part is an informed assessment (see day 4b in Table 3). Participants were given a list of sounds and visual design elements that they should evaluate before being exposed to the 4 true audio-visual combinations (VS1-VS4).

The experiment was introduced and guided by the same interviewer during all 4+1 sessions following a strict protocol. This guarantees that there was no bias caused by the way the experiment was introduced.

Table 3. Schedule for the Experiment (16 environments)

	Visual 1	Visual 2	Visual 3	Visual 4
Day 1 = Sound 1	VS1	V2-S1	V3- S1	V4- S1
Day 2 = Sound 2 (Non-inf.)	V1-S2	VS2	V3-S2	V4- S2
Day 3 = Sound 3	V1-S3	V2-S3	VS3	V4-S3
Day 4a=Sound 4	V1-S4	V2-S4	V3-S4	VS4
Day 4b =S1-S2-S3-S4 (Informed)	VS1	VS2	VS3	VS4

* Environments with bold letter (VS) correspond to the true-combination of Sound and Visual

1.3.3. Questionnaire

Participants were asked to experience the environment as a pedestrian within the urban context previously described. Immediately after each walk taken on day 1 till day 4a, the following

question was asked: (1) how would you rate your experience while passing this bridge to go from the city centre to the park? (Answers could be given on an 11-point linear scale with textual description of the endpoints: “very unpleasant” (-5) to “very pleasant” (+5)). After the 16 environments were evaluated (see non-informed in Table 3), participants were asked to do the 4 walks again (but now with the matching sounds: true-combination). This time however, they were well-informed about the visual and sound elements that could be of relevance and that they will be asked about after the experience. This way, it is expected that they will pay attention to both the sounds and visuals (see day 4b in Table 3). At the end of each walk the same question (1) was asked. Additionally, the participants were invited to rate each audio and visual element with the following two questions:

- (2a) Rate how much you liked the following visual elements in the urban environment: the colour of the pavement, the tiles on the pavement, the design of the barrier, the design of the urban furniture, the design of the bench, the design of the planters, the vegetation on the bridge, the openness of the space and the presence of other persons (answers could be given for each of these elements on an 11-point linear scale with textual description of the endpoints: “I did not like it at all” (-5) to “I liked it a lot” (+5)).
- (2b) Rate how annoying or pleasant these sounds were in the environment: the car passing by, the tram passing by, the highway and the birds (answers could be given for each of these elements on an 11-point linear scale with textual description of the endpoints: “very annoying” to “very pleasant”).

After the whole experiment, two questions assessing the opinion of the participants about the realism of the Virtual experience were posed:

- (3a) Rate how much you felt physically immersed in each environment (answers could be given on an 11-point linear scale with textual description of the endpoints: “I didn’t feel immersed at all” (-5) to “I felt totally immersed” (+5)).
- (3b) Rate how real this walking experience was (answers could be given on an 11-point linear scale with textual description of the endpoints: “Not realistic” (-5) to “Very realistic” (+5)).

1.3.4. Hearing test

A pure tone audiometric test was performed to check the hearing capabilities of each participant. The criterion was 25 dB maximum allowable hearing loss at threshold at the frequencies of 250, 500, 1000, 2000, 4000 and 8000 Hz. This objective test was complemented by a self-assessment: 3 participants reported abnormal hearing and their answers were excluded from the study.

2. RESULTS AND DISCUSSION

The presentation, analysis, and discussion of the results contain several parts. Firstly, the main question is addressed: does the sound environment influence the pleasantness of using a route even if the attention of the user is not focussed on sound. In addition, it is investigated whether different visual designs interact with the sound environment. Secondly, the effect of the participant being informed about the elements in the design – including sound – is assessed. Thirdly, the preference of the visual and sound elements present in the urban scene is evaluated. Finally, the feeling of immersion and realism of the Virtual Reality experience was asked for to check the ecological validity of the experiment.

For the first three questions, 71 respondents with good hearing capabilities out of 75 that completed the experiment were considered in the statistical analysis. For the final research question, only 42 participants answered question 3a and 3b and were considered in the analysis.

2.1. Influence of sound on the overall urban environment

For the first part of the experiment (non-informed), a multi-factor Analysis of Variance was undertaken with the non-informed results, which includes both the true and the non-true audio-visual combinations (Table 3). The dependent variable was the pleasantness and the independent variables were the person (ID) used as a random factor, the four different sound environments (S) and the four visual environments (V) (Table 4). There is no multi-collinearity due to the independence of factors. The distribution is close to a Gaussian one, slightly tailed to the lower responses with centre around a value of 1.5. The standard deviations of pleasantness rating for the 16 combinations Visual-Sound was within the range 1.20-2.36. There is no correlation between the variables by construction of the experiment since all the participants were exposed to all possible combinations of sounds and visuals.

Table 4. Summary of the multi-factor analysis of Variance (ANOVA) test. The pleasantness is the dependent variable. Only the non-informed responses are considered here. All combination (including the true combinations) between visual and sound are included.

Analysis of variance					
Source	Sum Sq.	d.f.	Mean Sq	F	Prob>F
ID (person)	1451.67	70	20.738	2.7	0
S (sound)	50.21	3	16.738	5.38	0.0014
V (visual)	702.13	3	234.043	41.12	0
ID*S	653.79	210	3.113	2.75	0
ID*V	1195.37	210	5.692	5.03	0
S*V	16.44	9	1.827	1.62	0.1072
Error	712.56	630	1.131		
Total	4782.17	1135			

The average pleasantness ratings on an 11-point scale from -5 to +5 are shown in Fig. 7. The different soundscapes considered are presented in colours and grouped per visual. The true-combinations are indicated with VS1, VS2, VS3, and VS4. The asterisk represents the cases that are significantly different from all the other cases for a given independent variable.

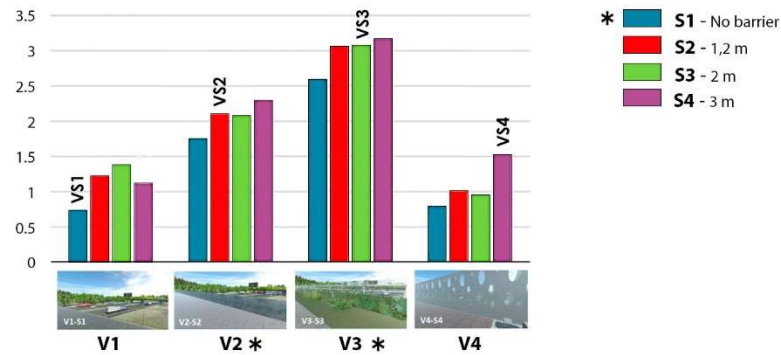


Fig. 7. Average pleasantness rating for all combinations of Sounds (S) and Visuals (V). Non-informed answers.
*=Significantly different from the rest of the cases considered.

The sound environment affects the pleasantness rating of the experience of passing the bridge in a statistically significant way ($F=5.38$ $p<0.0014$). Thus, the sound environment influences overall pleasantness even when a direct comparison is not possible since different sounds were presented on different days.

Sound, however, has a smaller effect than the visual environment as the total amount of explained variance is smaller. A major influence of the visual setting was found. Results in Table 4 show that differences in pleasantness rating between the four visuals considered are strongly statistically significant ($F=41.12$, $p<0.001$). The fact that the 4 visuals are displayed on the same day needs to be considered in this comparison since it enables to directly compare them.

When considering interaction terms between person (random factor) and sound or visual, we notice that both are statistically significantly different from a zero interaction effect. Persons

react differently both to sound and visual in their pleasantness rating. Visuals have a somewhat stronger interaction with persons than sound.

Finally, an interaction effect between sound and visual, without considering personal factors, was found. However, the 5 % significance level is not reached for this interaction term. The aforementioned independent factors and their interaction terms explain a great deal of the variance since the remaining error is rather limited.

Post-hoc analysis reveals that visuals V2 and V3 are significantly different from the rest. The great majority of participants rated the vegetated visual (V3) by far as the most pleasant one. This result agrees with previous work confirming the pleasant perception of vegetation (Hong & Jeon, 2013; Hong & Jeon, 2014; Van Renterghem & Botteldooren, 2016). The least pleasant visuals were the conventional (V1) and the whimsical (V4). The latter are not statistically different.

The mean pleasantness rating of S1, considering all visuals, is significantly different from the rest of the sound environments (Figure 7). This indicates that the main difference is found between the sound field without traffic noise reduction and the ones with a noise barrier. The noisiest soundscapes (S1, S2, and S3) get the lowest ratings in pleasantness when combined with visual V4. However, the rating increases for the SV4 case, where visual matches sounds. This could be explained – to some extent – by the congruency hypothesis (Ge & Hokao, 2005; Lindquist, Lange, & Kang, 2016). The large reduction in level provided by a strong visual barrier matches people's expectations, positively affecting general pleasantness. The combination V1S4 could have a similar cause, but now leading to reduced pleasantness.

In a relative way, the 1.2 m height barrier (S2) increases pleasantness much more than the 2 m barrier (S3) or the 3 m barrier (S4). The noise reduction that the 1.2 m noise barrier provides to the pedestrian is already quite high, despite the small height of the barrier (Table 1). Higher barriers achieve a slightly larger reduction. However, incrementing 1.2 m to the 2 m barrier provides only an additional 3 dB(A) of overall noise reduction (Table 2).

The above analysis allows drawing a relevant conclusion: to increase the pleasantness for walkers on this bridge, only increasing the height of a barrier to achieve higher noise attenuation is not very efficient.

2.2. Focused analysis of the audio-visual environment:

In the second part of the experiment, participants were asked about specific elements of the visual and sound environment prior to experiencing the walk and hence are expected to pay attention to sounds and visuals (i.e. the informed experiment).

The ratings between being uninformed and informed for each of the four true-combination environments are juxtaposed in Fig. 8. Results show that pleasantness is rated slightly lower when people are informed.

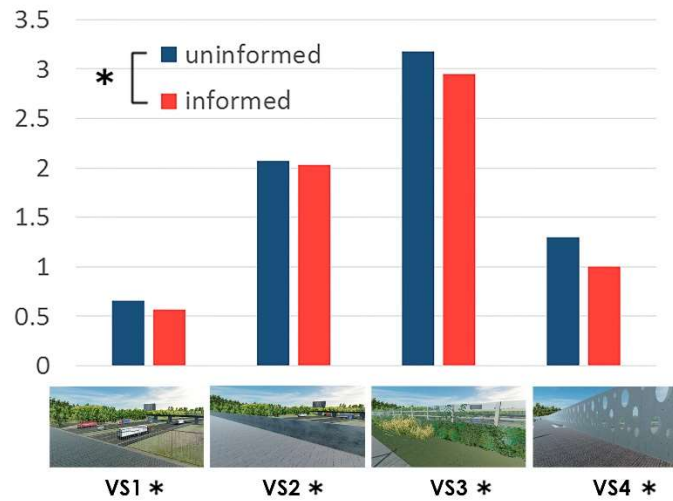


Fig. 8. Comparison of pleasantness ratings between being non-informed and informed about the assessment of visuals and audio elements. Only true combination of visual-sound. The asterisk represents the cases that are significantly different from all other cases (within a single factor).

A second multi-factor ANOVA assesses only the results from the true combinations between sound and visual (Table 5). Being informed or not is coded to an additional variable and person (ID) is considered again as a random factor. A general statistically significant difference between being informed and non-informed is found, obtaining a lower pleasantness rating when informed ($F_{0,6.99}$, $p=0.01$). Most likely, people will focus more on the highway noise and could take it stronger into account while rating. Similar effects were found in other noise-related studies (Van Renterghem, Bockstael, De Weirt, & Botteldooren, 2013).

There are no significant interaction effects between being informed and the audio-visual design (Table 5) implying that although being informed leads to lower pleasantness ratings, this lowering is independent of the audio-visual design that is being evaluated.

Table 5. Summary of the multi-factor analysis of variance (ANOVA) test. The pleasantness is the dependent variable. The non-informed and informed values are considered. Only the true-combination between sound and visual are included. Person ID is included as a random factor.

Source	Sum Sq.	d.f.	Mean Sq	F	Prob>F
ID (person)	699.39	70	9.991	2.31	0
SV (sound and visual)	478.29	3	159.43	40.55	0
Informed	10.17	1	10.169	6.99	0.0101
ID * SV	825.71	210	3.932	3.68	0
ID * Inf.	101.83	70	1.455	1.36	0.0501
SV * Inf.	4.41	3	1.469	1.37	0.2517
Error	224.59	210	1.069		
Total	2344.39	567			

When sound and visual matches (true-combination), the four different environments become more differentiated being all significantly different from each other in pleasantness rating. The order of preference of the environments (SV3, SV2, SV4, and SV1) is similar to the non-informed assessment, except for the differentiation of the last two cases, being the least pleasant environment SV1, correspondent to an absence of a traffic noise reduction measure and a conventional urban design. This case is similar to the current situation, and stresses the necessity of renovation of the bridge. Additionally, only in the true-combination of sound and visual, people appreciate the high barrier more than the open visual.

In order to further understand the differences in the preference of the four environments, the participants were questioned about the dominant sound and visual elements (Question 3a and 3b). The liking rate of each visual and sound element present in each urban proposal is shown in Fig. 9. Only the true-combinations between sound and visual are included.

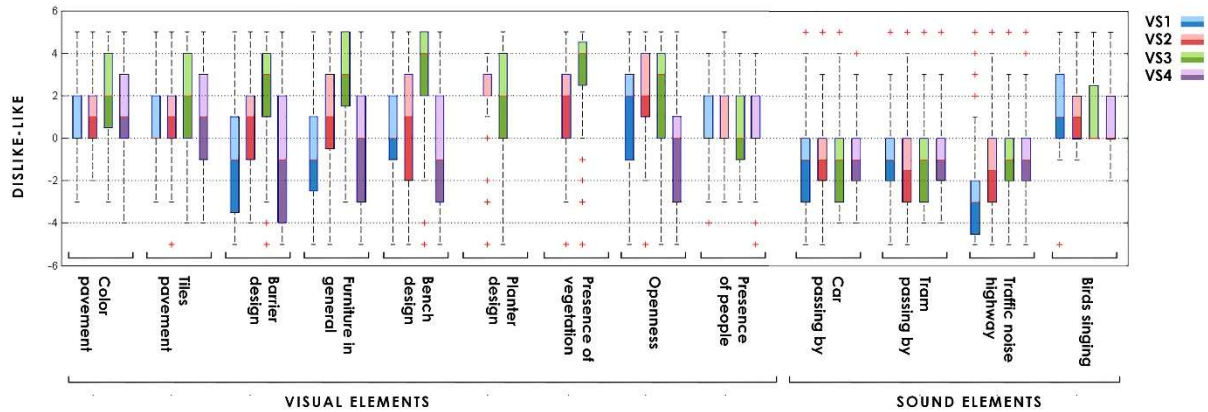


Fig. 9. Liking ratings for visual and sound elements. True-combination Visual-Sound. Informed. Median and quartiles are shown as blocks together with whiskers extending to 1.5 times the interquartile distance.

2.2.1. Visuals:

Some visual elements have very different ratings in the different urban settings, whereas others have similar ratings in all cases. The barrier, furniture and bench design were perceived very differently. The degree of liking of these elements agrees with the general pleasantness rating of the experience (see VS1, VS2, VS3, and VS4 in Fig. 8), indicating the potential of these elements to contribute to the pleasantness of the experience. The preference of pavement colour and tiles does not vary in the different models, but they are slightly more preferred in the vegetated environment (VS3), which can be due to the attractiveness of natural pavements made of wood and grass. The openness of the landscape gets similar rates with exception of the fourth Environment (VS4), where the open view is considerably reduced and the tallest barrier is strongly disliked. This confirms the findings from other research where the sonic ambiance was perceived in a positive way when the visual space is kept open (Marry & Defrance, 2013). Furthermore, the liking is similar for small barriers and barriers including glass allowing for an open view. The first environment gets a contradictory slightly lower rating of openness despite it is the case with the most open view. This rating might show that excessively open space could

negatively affect the personal preference. In this case, the reason could be the light balustrade, which provides a feeling of unsafety to falling down from the bridge. The preference of the presence of other people is very similar in all cases. It only gets a slightly lower liking in the green case (VS3), entering the negative part of the rating scale. The planters and vegetation which are only present in the second and third case always get positive ratings, especially in the 3rd environment (VS3).

2.2.2. Sounds:

The liking ratings of the sound elements show that the car, tram and highway were rated negatively while the birds sound was rated positively. Previous work demonstrated the importance of bird songs to enhance soundscape pleasantness (Coensel, Vanwetswinkel, & Botteldooren, 2011). All sounds got similar ratings in all environments except for the highway sound. This is logical since the sounds are the same in each environment except for the highway noise. Therefore, the different visual settings don't influence considerably the preference of individual sounds. The rating of the highway sound is consistent with the sound pressure level, showing that people accurately perceived the traffic noise reduction when they were asked to focus on environmental sounds.

2.3. Realism of the virtual experience

The Virtual Reality model was considered to be immersive by the participants as shown in Fig. 10. Also the rating of realism showed mostly positive values. However, especially the youngest participants were the most critical ones. They pointed to the limited resolution of the Oculus screen. It is expected that the technological evolution in such instruments will strongly improve

in the near future, further increasing the realism of the visual experience. It can therefore be concluded that Virtual Reality is a realistic mean to assess the quality of future urban design.

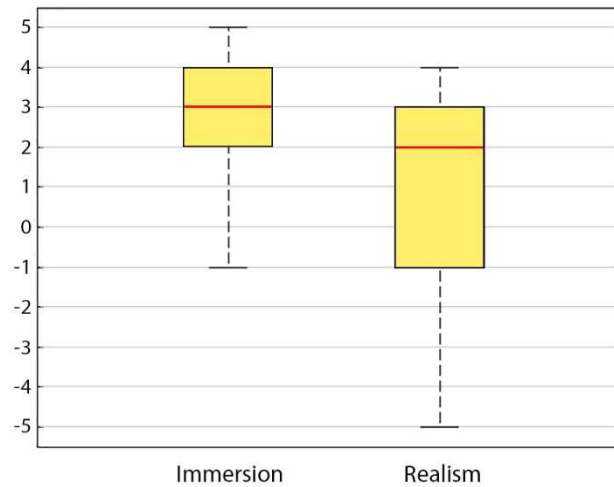


Fig. 10. Rating of Feeling of Immersion in the Virtual Urban scene and Realism of the walking experience in the Virtual Reality.

3. CONCLUSIONS

Four different visual designs and four sound environments for a bridge connecting the inner city to a large park were compared in a 3D virtual audio-visual environment by 71 persons that had no prior knowledge of the place. During the experiment, the participants were asked to rate their experience while passing this bridge to go from the city centre to the park on an 11-point scale with end points “not at all pleasant” to “very pleasant”.

To investigate the influence of sound on the overall appreciation of this public space in an ecologically valid context where users would not particularly pay attention to sound, a careful experimental design was needed. During each day of the experiment, participants experienced the four visual designs one after the other combined with only one sound design. On subsequent days the same set of four visual designs was presented together with another sound design.

Sound was not mentioned in the introduction and participants did not enter an anechoic room or any other environment that could reveal our interest in the sound environment. Even in this non-focussed context, a statistically significant effect of the sound environment on the overall appreciation was found. The interaction of visual design and sound design was not statistically significant at the 5% significance level. There is, however, a significant interaction between person and visual, and person and sound design. The pleasantness rating of crossing the bridge shows an increasing trend with decreasing noise level and thus increasing barrier height for noise levels that can be found above multilane highways when averaged over all visual designs.

After asking the participants about different visual and sound components that could have been noticed, the same experiment was repeated but this time only the 4 physically realistic combinations of sound and vision were used. It can be expected that participants now paid stronger attention to these individual components as they were informed that they would be asked about them. This resulted in a small but statistically significant reduction in pleasure judgement. The relative ranking of the designs nevertheless remained the same.

In the experimental design, the visual design was part of a direct comparison. The visual design has a strong statistically significant influence on the rated pleasure in passing the bridge. The vegetated design integrating a 2 m high barrier seems most appreciated as a walkway towards the park. The more urban design integrating a 3 m high barrier is not rated as pleasant as the vegetated design. When combined with the matching reduction in highway noise, this audio-visual situation is still rated statistically significantly more pleasant than the conventional design. However, when the matching noise reduction is not included, this whimsical design does not outperform the conventional one. Looking from the perspective of traffic noise reduction it can be concluded that noise barriers placed on a bridge across a highway are useful, but that the

visual design of such a noise reduction measure has to be given ample consideration. This is important for urban practice: instead of further increasing noise barrier height, improving the visual design of a low barrier could be more effective in increasing pleasantness.

Considering the specific elements of the audio-visual design that are liked or disliked, the expected outcomes are found. Highway sound is particularly disliked in the original situation but there is little difference between the three designs with noise barriers. Barrier design, street furniture and the presence of green are the main elements that are liked in the vegetated design. The (lack of) openness is the main factor that is disliked for the design including the 3 m high barrier.

The new methodology for comparing the quality of renovation alternatives for an urban bridge, and by extension any urban public space, was shown to be sensitive enough for comparing these alternatives. It is also an approach that is understandable by the public at large. Participants rated the experience of the virtual environment as rather realistic and immersive. This study nevertheless did not prove in a strict sense that audio-visual designs that are appreciated as pleasant in a virtual context would also lead to real environments that are also appreciated as more pleasant.

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